Transmission-Line Based Modeling for Conformal Shielding in Advance System-in-Package (SiP)

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Abstract—**In order to efficiently eliminate the noise generated from high-speed integrated circuits, the conformal shielding technology is gradually utilized in advanced System-in-Package (SiP). In this paper, a prediction method based on the transmission-line theory is proposed for evaluating shielding effectiveness (SE) of conformal shielding on SiP. SE measurement of various coating materials is done and presented. By using 4-μm copper, the measured SE successfully demonstrates about 45 dB at the operating frequency of 1 GHz. The proposed model shows a good agreement compared with measured results from 0.01 GHz to 1 GHz.**

I. Introduction

The high-speed operation of digital circuits in System-in-Package (SiP) may cause severe electromagnetic interference (EMI) problems. To reduce the unintended electromagnetic emissions from IC devices, electromagnetic compatibility (EMC) design plays an important role. In the past, the shielding lid was a common solution to solve EMI problems in SiP; however, high cost and heavy weight cannot meet the requirements in mobile designs. Recently, conformal shielding technology has been widely studied and researched [1], [2]. To do conformal shielding, several techniques such as sputtering, vaporization, and electro-/electro-less plating, have been developed to coat thin metallic sheets on SiP modules. Compared with using shielding lids, conformal shielding technology not only owns the advantages of low cost and light weight, but also provides comparable shielding performances.

Shielding effectiveness (SE) is a typical index to evaluate the shielding performance. Field-distribution method [3] and the equivalent transmission-line method [4], [5] are previously employed to calculate SE of metallic sheet. Field-distribution method solves Maxwell equations through boundary conditions; on the other hand, the equivalent transmission-line method utilizes network analysis to calculate the metallic sheet performances. In previous works, it is usually assumed that the uniform plane wave propagates within the free space and is incident on an infinite large shielding sheet. In that case, the radiating and receiving wave impedances are identical to be 377 Ω in the far-field region, which assumption is hardly to be met in the circumstance of SiP.

This paper proposes a new prediction method based on transmission-line theory to evaluate SE of conformal shielding on SiP. For the conformal shielding on SiP, the wave impedances of radiating and receiving sources, in the near-field region, are different and complex values. To deal with the complex wave impedances, the power wave normalization technique is introduced [6].

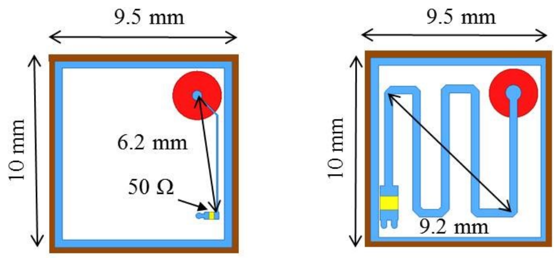

Fig. 1 Configurations of layout patterns: left-handed side is straight-line type and right-handed side is meander-line type.

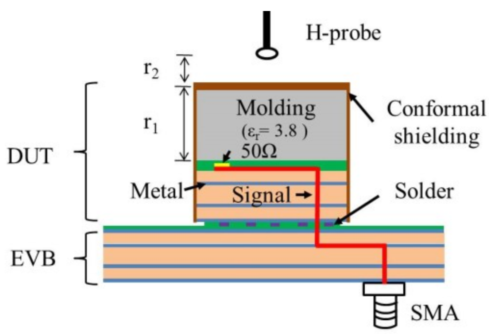

Fig. 2 Structure of the test vehicle.

II. Test Vehicle Designs and Modeling Analysis

A. Test Vehicle Designs

Two types of layout patterns were designed for SE evaluation. As shown in Fig. 1, one is straight-line type and the other is meander-line type, while the corresponding areas are both 10 × 9.5 mm^2. For broadband matching, characteristic impedances of both types are designed as 50 Ω and terminated by a matched resistor. The structure of test vehicle is illustrated in Fig. 2, which consists two parts: the device under test (DUT) and the evaluation board (EVB). For the DUT, the patterns of straight and meander lines are placed on the top

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metal layer as the radiating sources. Since the size of DUT is too small to feed signal directly, it is necessary to adopt the EVB for interconnecting the DUT with a SMA connector. For the design of EVB, reducing the energy leakage of signal feeding trace is very critical; thus, the stripline structure is used. To realize a conformal shielding on SiP, a thin metallic sheet is coated on DUT using sputtering technology.

B. Transmission-Line Based Modeling

The currents flowing on the straight/meander line and returning from the ground below form as a current loop. Since the longest diagonals of the straight and meander lines are small enough compared with the corresponding electrical lengths, they can be considered as small loop antennas. The condition of small loop antenna is given by [7]

$$2\pi b < \lambda / 10, \quad (1)$$

where 2*b* is the diameter of the small loop antenna; λ is the guided wavelength in the medium. As plotted in Fig. 1, in our straight- and meander-line cases, 2*b* are 6.2 mm and 9.2 mm, respectively. On the other hand, a magnetic probe is utilized to measure the emission and can be also considered as a small loop antenna in the near-field region.

The schematic of the near-field scenario and its equivalent transmission-line model are drawn in Fig. 3. The wave impedance of a small loop antenna in the near-field region can be described as

$$Z_{wi} = -\frac{\eta_0}{\sqrt{\varepsilon_{ri}}}\frac{j/\beta r_i + 1/(\beta r_i)^2}{j/\beta r_i + 1/(\beta r_i)^2 - j/(\beta r_i)^3}, \quad (2)$$

where η_0 is the intrinsic impedance of free space, ε_{ri} is the relative permittivity, β ($= \omega\sqrt{\varepsilon_{ri}}/c_0$) is the phase constant of the propagating media, r_i (i = 1 or 2) is the distance from radiating source to the shielding sheet. For Z_{w1}, the radiating source (the straight/meander line) propagates in the molding with ε_{r1} = 3.8 and r_1 = 0.91 mm. For Z_{w2}, the receiving source (the magnetic probe) propagates in the free space with ε_{r2} = 1 and r_2 = 0.3 mm.

Despite the equivalent transmission-line method is utilized for uniform plane waves, it still can approximately evaluate SE. With regard to the shielding material which is usually a good conductor, the propagation constant (γ) and the equivalent characteristic impedance (η_c) are expressed as

$$\gamma \approx (1+j)\sqrt{\pi f \mu \sigma}, \quad (3)$$

$$\eta_c \approx \sqrt{\frac{j2\pi f \mu}{\sigma}} = \frac{\gamma}{\sigma}, \quad (4)$$

where μ and σ are the permeability and conductivity of the shielding material, respectively [4].

With the conventional network analysis, the terminal impedances at the ports are equal and real values. However, Z_{w1} and Z_{w2} are different and complex values, the transmission coefficients have to be derived by using the power wave normalization technique. According to [8], there is a two-port scattering matrix [S_{11}, S_{21}, S_{12}, S_{22}] and its terminal

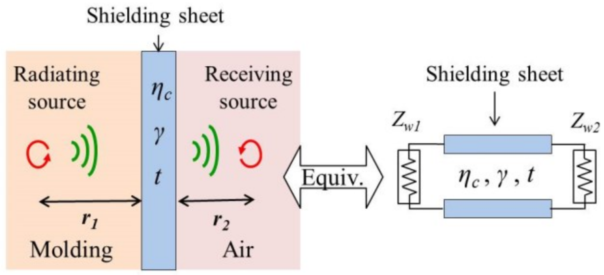

Fig. 3 Schematic of the near-field scenario and its equivalent transmission-line model.

impedances are both Z_0, so that the normalized transmission coefficient can be expressed as

$$S_{21}' = N\cdot(1-\Gamma_1)\cdot\left[\frac{S_{21}}{(1-\Gamma_2^*)}\frac{1-\Gamma_2 S_{22}}{\Delta x} + \frac{S_{22}-\Gamma_2^*}{(1-\Gamma_2^*)}\frac{\Gamma_2 S_{21}}{\Delta x}\right], \quad (5)$$

where

$$N = \sqrt{\left|\frac{\mathrm{Re}(Z_{w1})}{\mathrm{Re}(Z_{w2})}\right|}, \quad (6)$$

$$\Gamma_1 = \frac{Z_{W1} - Z_0}{Z_{W1} + Z_0}, \quad (7)$$

$$\Gamma_2 = \frac{Z_{W2} - Z_0}{Z_{W2} + Z_0}, \quad (8)$$

$$\Delta x = (1-\Gamma_1 S_{11})(1-\Gamma_2 S_{22}) - \Gamma_1\Gamma_2 S_{12} S_{21}. \quad (9)$$

Finally, SE of the proposed model is defined as

$$\mathrm{SE\ (dB)} = 20\log_{10}\left|\frac{S_{21\ ,without}'}{S_{21\ ,with}'}\right|, \quad (10)$$

where $S_{21}'_{,\ without}$ and $S_{21}'_{,\ with}$ are the normalized transmission coefficients without and with the shielding materials, respectively.

III. Measurement Setup and Result Discussion

A. Measurement Setup

To evaluate SE of the conformal shielding on SiP in a near-field region, a measurement setup is established as demonstrated in Fig. 4. The measurement uses a HP-83650P signal generator, a MITEQ pre-amplifier (0.01-3000MHz), an R&S FSP40 spectrum analyzer, and a HITACHI EMV-200 magnetic-field scanning machine with the computer-aided software. In order to get the location of maximum radiation emission, the magnetic probe is moved on the top of the package by the spatial resolution of 1-mm step along both *x* and *y* directions. SE can be evaluated by calculating the differences between DUT with and without shielding materials.

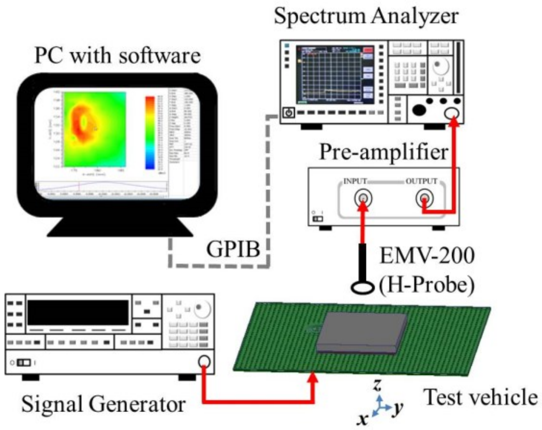

Fig. 4 Measurement setup.

TABLE I
RELATIVE PARAMETERS OF SHIELDING MATERIALS

Frequency [GHz]	Ni	Cu
0.01	12.92 – j 1.14	0.999991
0.10	9.45 – j 5.85	
0.50	4.63 – j 1.96	
1.00	3.64 – j 3.05	
Conductivity (S/m)	3.3×10^{6}	5×10^{7}

For the near-field measurement, the measured SE (SE_M) is defined as the following expression at the location of maximum radiation emission.

$$\mathrm{SE_M}\ (\mathrm{dB}) = 20\log_{10}\left|\frac{H_{without}}{H_{with}}\right|. \qquad (11)$$

B. Comparison between Modeled and Measured Results

In this paper, two shielding materials with different sheet thicknesses are studied. The characteristics of materials are listed in Table I. Due to the eddy current loss, the permeability of nickel decreases when frequency increases. The calculated and measured SEs of straight and meander lines are depicted in Fig. 5. Compared with the measured data, the results of proposed method show a good agreement and high accuracy. The deviations are below than 10 dB for the most cases. Regarding to fair accuracy of the straight-line with 4-μm copper, the reasons may come from the non-ideal fabrication tolerance and measurement errors.

To discuss the measured SEs of copper and nickel, it is worth taking the best cases for examples. For meander line with 4-μm copper, the measured SE of the conformal shielding on SiP is 10, 23, 37, and 44 dB at 0.01, 0.1, 0.5, and 1 GHz, respectively. On the other hand, for meander line with 15-μm nickel, the measured results are 13, 25, 34, and 37 dB 0.01, 0.1, 0.5, and 1 GHz, respectively. Surprisingly, the performances of nickel are poorer than 4-μm copper, even for 15-μm nickel. The reason is the characteristics of nickel are changed after sputtering and the permeability is not high as expected.

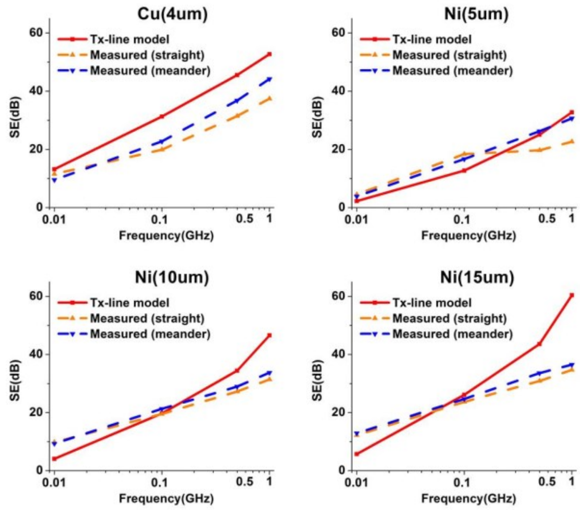

Fig. 5 Measured and modeled SE results with different coating materials.

IV. CONCLUSIONS

To deal with the conformal shielding on SiP circumstance, the prediction method based on the transmission-line model and power wave normalization technique is proposed. For verification, copper- and nickel-shielded test vehicles are calculated and measured based on the near-field measurement. Proposed method demonstrates a good agreement for evaluating SE performances from 0.01 to 1 GHz.

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